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Angular distributions of proton groups from the reaction $B^{10}(d, p)B^{11}$

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With 7 figures in the text

Introduction

By comparing experimentally obtained angular distributions for (d,p) and (d,n) reactions with those derived from the assumption of a stripping process, information about spin and parity of the final nucleus can often be obtained.

In the case of the reaction $B^{10}(d,p)B^{11}$ several measurements of angular distributions have been done in the last few years (refs. 1–7). However, the distributions of the groups corresponding to the levels 6.81 and 7.30 MeV in B^{11} have not been reported. The protons to the former level have not been separated from those to the 6.76 MeV level. In the present measurement angular distributions corresponding to the three levels are given for a deuteron energy of 0.800 MeV. This is a case in which high energy resolution is necessary and it is thus suitable for the equipment at the Nobel Institute (refs. 8, 9). The interpretation of the distributions is simplest when the deuteron energy is rather high, but it is possible to determine theoretical curves also for lower deuteron energies, although the calculations are more involved in this case (see e.g. refs. 10–13).

Experimental procedure

The deuteron beam was obtained from the Cockcroft–Walton accelerator of the Nobel Institute and was bent by the magnetic analyzer. Protons produced in the reaction were studied with the rotatory high resolution double focusing spectrometer. The measuring equipment has been described in refs. 8 and 9. However, as described in the appendix, some small changes have been made in the arrangements for measuring the incoming beam and for screening magnetically and electrically. The detection of the protons having passed the spectrometer was made with 50 μ nuclear emulsion plates, type Ilford C2, and the tracks were counted by scanning with a microscope. In Fig. 1 are shown typical spectra for the three proton groups from $B^{10}(d,p)B^{11}$ which were studied. In the peaks 6.76 and 7.30 MeV resp. about 1500–2000 tracks were counted, being roughly half of the total number. For the determination of the very small 6.81 MeV peak in proportion to the 6.76 MeV peak some plates were exposed much more than was the case in Fig. 1.

The differential cross-section for a certain angle compared with that for a reference angle was obtained by several alternating exposures in the way described in ref. 9. Generally the spectrometer angles $\varphi = 90°$, $60°$ and $30°$ (see the appendix) were

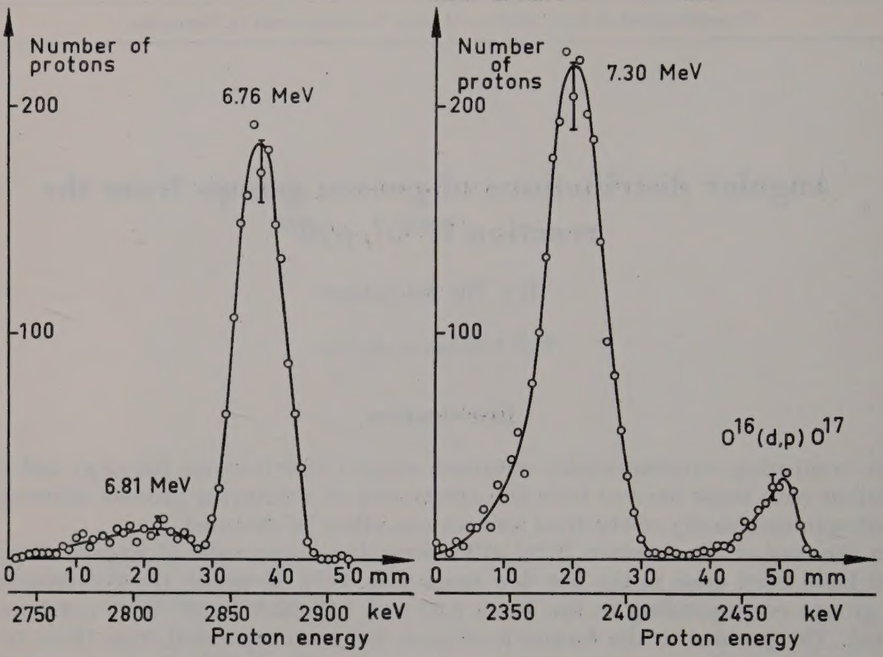

Fig. 1. Typical spectra of protons from $B^{10}(d,p)B^{11}$ leading to the states 6.76, 6.81 and 7.30 MeV of B^{11}. For the first two groups a layer of natural boron on a 15 mg/cm² Al foil was used as target and for the last group 10 μg/cm² enriched B^{10} on 2 μ Au plated on Cu. $\varphi = 90°$. $E_d = 800$ keV. The number of tracks/0.4 mm of the plate is put as ordinate and statistical deviations are indicated. The absolute position of the energy scale is approximate.

used as reference settings. The yields in the directions $\varphi = 90°$ and $\varphi = 60°$, as well as $\varphi = 90°$ and $\varphi = 30°$ were compared in at least two separate measurements to get better accuracy in joining the different parts of the distribution curve. The 6.76 and 6.81 MeV groups were measured from $\varphi = 0°$ to $\varphi = 135°$ and the 7.30 MeV group from $\varphi = 25°$ to $\varphi = 135°$, generally in steps of 7.5°.

Vacuum evaporation of several boron compounds was tried in order to get a useful target. However, the best result was obtained with natural elementary boron on thin foil backings. The boron was evaporated from a carbon crucible. For the 6.76 and 6.81 MeV groups an Al foil, 0.15 mg/cm², was used with a boron layer of one or two μg/cm² and it was exposed in most cases to about 1000 μC deuterons. For the 7.30 MeV group, on the other hand, it was not possible to make use of such a target for all angles. The trouble was due to the contamination of the very strong ground state group from $O^{16}(d,p)O^{17}$ for spectrometer angles $\leq 90°$. Therefore, in that case a 10 μg/cm² layer of enriched B^{10} on a 2 μ Au-backing plated on Cu was used. With that target—obtained from A.E.R.E., Harwell—the O^{16}-peak was relatively weak (Fig. 1) and it was separated from the B^{10}-peak for $\varphi \geq 60°$. For $\varphi < 60°$ the two peaks were mixed and it was necessary to subtract the O^{16}-protons. For that reason a part of the angular distribution of the latter was measured using as target the oxide coat on a pure Al foil (Fig. 3). The B^{10}-target was exposed to about 500 μC.

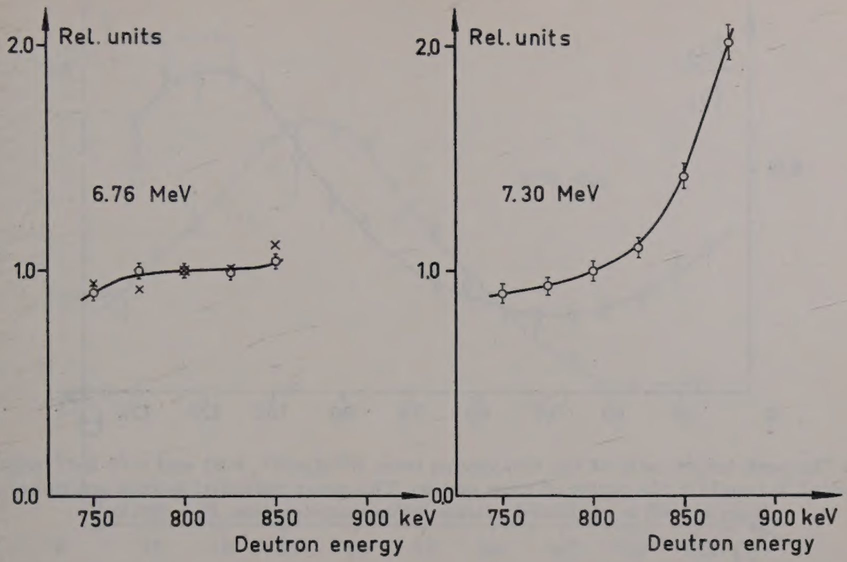

Fig. 2. Excitation curves for the 6.76 and 7.30 MeV proton groups from $B^{10}(d,p)B^{11}$ in the neighbourhood of $E_d = 800$ keV. $\varphi = 90°$. Statistical deviations are indicated. The crosses give the values for the 6.81 MeV group that were obtained by taking the peak-height ratio of the 6.81 and 6.76 MeV groups. The deviations from the 6.76 MeV points are within the limits of error.

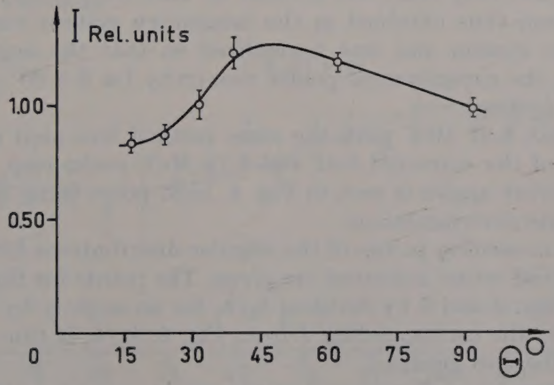

Fig. 3. A part of the angular distribution for the ground state protons from $O^{16}(d,p)O^{17}$ determined to make possible the subtraction of the oxygen protons from the 7.30 MeV boron group. Cf. the text to Fig. 5.

Before the deuteron energy to be used was decided, the excitation functions for the proton groups were measured in the neighbourhood of 800 keV and for $\varphi = 90°$. Thereby the procedure was analogous to that for the angular distribution measurements. The reference setting was 800 keV. The result is given in Fig. 2. It is seen that the curves are flat at 800 keV.

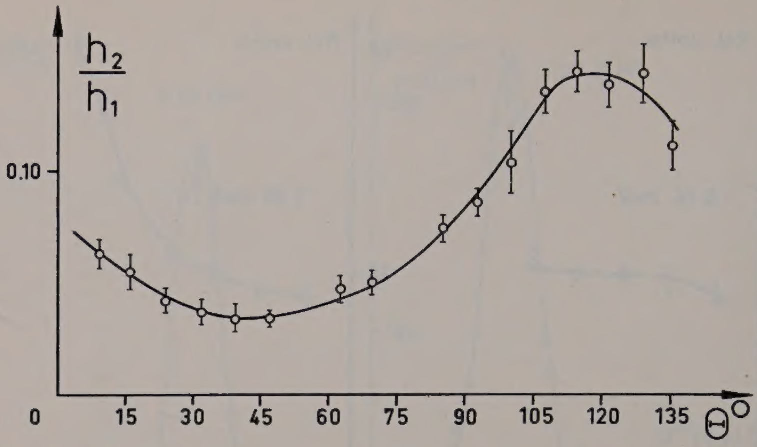

Fig. 4. The peak-height ratio of the two groups from $B^{10}(d,p)B^{11}$, 6.81 and 6.76 MeV resp., as a function of the angle in the center of mass system. The errors indicated include statistical deviations as well as estimated extrapolation uncertainties. $E_d = 800$ keV.

Calculations and results

Before a peak was summed up and the background (usually 2–4%) was subtracted, the number of proton tracks was corrected for the position of the tracks on the plate (ref. 14). The sum was divided by the corresponding deuteron charge given to the current integrator and that ratio was divided by that for $\varphi = 90°$. The relative differential cross-section thus obtained in the laboratory system was transformed to the center of mass system and was normalized so that the angular distribution curve best fitting the experimental points was unity for $\theta = 90°$ (θ is the angle in the center of mass system).

For the very weak 6.81 MeV peak the same method was used as in ref. 15. The height ratio h_2/h_1 of the corrected 6.81 and 6.76 MeV peaks resp. was determined. The result for different angles is seen in Fig. 4, each point being the mean value of at least two separate determinations.

In Figs. 5–7 the measuring points of the angular distributions for the three proton groups with statistical errors indicated are given. The points for the 6.81 MeV group is obtained from Figs. 4 and 5 by dividing h_2/h_1 for an angle φ by h_2/h_1 for 90° and then multiplying by the corresponding I from Fig. 5. h_2/h_1 is thus put equal to the intensity ratio of the two groups.

The 6.76 MeV curve has a pronounced maximum at about $\theta = 50°$ and seems to be isotropic for $\theta > 115°$. The 6.81 MeV curve has a flat maximum at about $\theta = 110°$. Finally, the 7.30 MeV curve increases to a maximum at about $\theta = 130°$.

The angular distribution functions were evaluated in a series of Legendre polynomials of the first kind:

$$I(\cos\theta) = \Sigma a_i P_i(\cos\theta).$$

The coefficients

$$a_i = \tfrac{1}{2}(2i+1)\cdot\int_{-1}^{+1} I\cdot P_i d(\cos\theta)$$

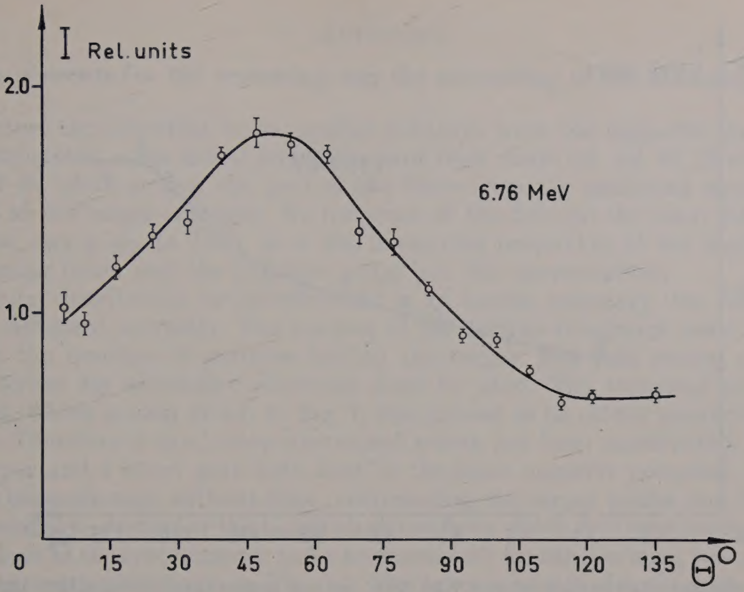

Fig. 5. The angular distribution of the 6.76 MeV proton group from $B^{10}(d,p)B^{11}$ (i.e. the group leaving B^{11} in the 6.76 MeV state). $E_d = 800$ keV. $I(90°) = 1.00$. θ is the angle in the center of mass system and statistical deviations are indicated.

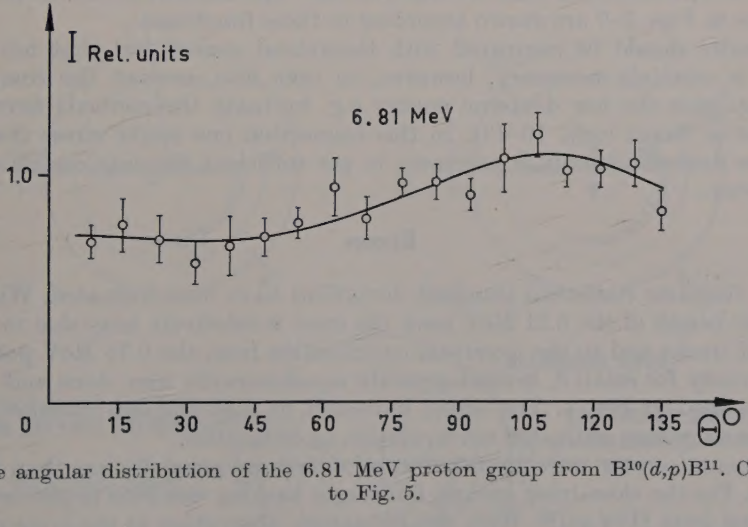

Fig. 6. The angular distribution of the 6.81 MeV proton group from $B^{10}(d,p)B^{11}$. Cf. the text to Fig. 5.

were calculated by 20-part numerical integration. An isotropic extrapolation was thereby made to θ-values in the neighbourhood of which no experimental points are given. The results for the groups 6.76, 6.81 and 7.30 MeV are resp.:

$$\begin{aligned}
I_1 &= 1.09 + 0.65P_1 - 0.46P_3 - 0.30P_4 - 0.08P_6,\\
I_2 &= 0.90 - 0.14P_1 - 0.20P_2 + 0.18P_3,\\
I_3 &= 1.09 - 0.46P_1 + 0.14P_3 - 0.23P_4 + 0.12P_5 - 0.05P_6.
\end{aligned}$$

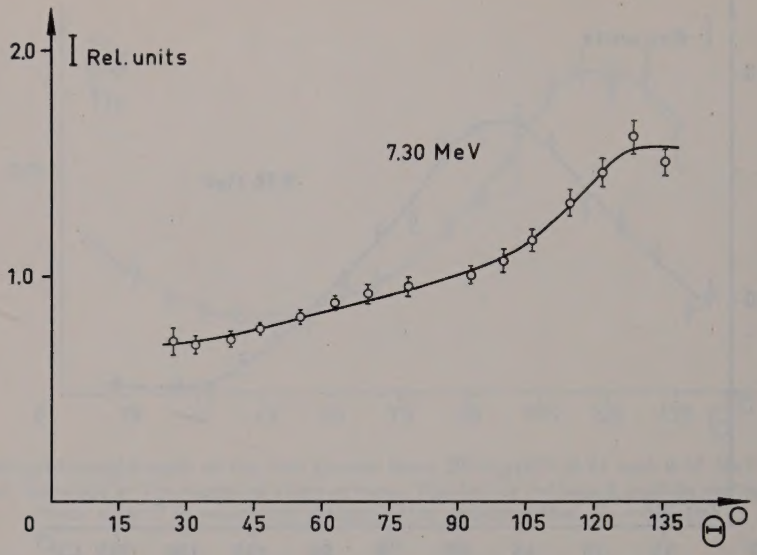

Fig. 7. The angular distribution of the 7.30 MeV proton group from $B^{10}(d,p)B^{11}$. Cf. the text to Fig. 5.

Terms have been excluded that are less than the experimental errors for all θ-values. The curves in Figs. 5–7 are drawn according to these functions.

The results should be compared with theoretical curves, but that has not been done. It is certainly necessary, however, to take into account the complications depending upon the low deuteron energy e.g. by using the methods developed by Tobocman or Grant (refs. 10–13). In this connection one might stress that often a rather low deuteron energy is necessary to get sufficient absolute resolution with a spectrometer.

Errors

In the diagrams statistical standard deviations have been indicated. When determining the height of the 6.81 MeV peak the error is relatively large due to the small number of tracks and to the uncertain contribution from the 6.76 MeV peak. Therefore, especially for small θ, several separate measurements were done and the mean value was used in Fig. 4. The errors indicated in that diagram include statistical deviations as well as estimated extrapolation uncertainties.

Instrumental errors were discussed in ref. 9 and are generally less than the statistical ones. For the close-lying groups, foil target backing was used to prevent a strong background from $H^2(d,p)H^3$. With the B^{10}-target, absorption in the layer and variations in E_d gave an error in the yield of less than 3% for the 7.30 MeV protons at $\varphi = 90°$ (cf. Fig. 2).

Uncertainties in the counting of the tracks are probably not important.

APPENDIX

Arrangements for the screening and the measuring of the incoming beam

To protect the incoming beam against influence from the magnetic stray-field of the spectrometer, a mu-metal screen has now been made (cf. ref. 9). It consists of a 4 mm Ni–Fe plate around the part of the beam from the analyzing magnet to the entrance of the target chamber. No influence of the field on the beam has been observed for any φ up to 135° (φ is the horizontal projection of the angle between the incoming beam and the particles going into the spectrometer).

In angular distribution measurements it is, of course, necessary that the incoming beam is measured correctly. The reading of the current-integrator must be proportional to the number of particles hitting the target. For that reason a negative-voltage screen for secondary electrons must be used. The screening arrangement first used, which is seen in ref. 9, Fig. 7, has proved to be rather unpractical during the runs. Therefore a new, more convenient screen has been constructed. It consists of an upper and a lower part both kept at the same negative potential. The upper part is a brassnet-cage without floor, surrounding the target holder and fixed in the upper, rotatable section of the target chamber from which it is electrically insulated. It has a hole to the spectrometer and a horisontal slit for the incoming beam. The position is schematically shown in Fig. 1 A. The lower screen is of lucite with a conducting silverpaint coating on the inside and covers the bottom and the walls of the lower, fixed part of the target chamber. It has a hole for the incoming beam. The counting

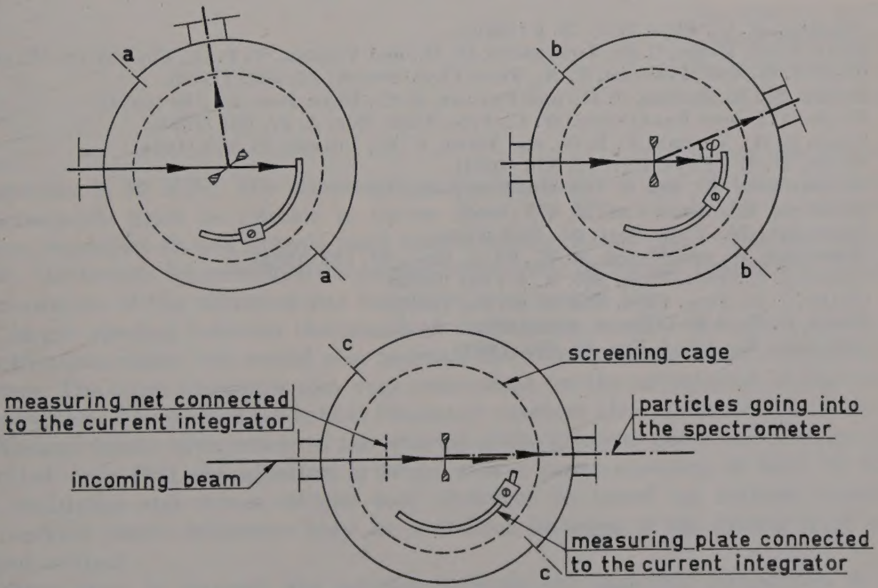
a
a
b
b
φ
c
c
screening cage
measuring net connected to the current integrator
particles going into the spectrometer
incoming beam
measuring plate connected to the current integrator

Fig. 1 A. The measurement of the incident beam intensity when the target has a thin foil backing. For $\varphi > 10°$ a metal plate is put behind the foil and for $\varphi \leq 10°$ a small-meshed metal net in front of the foil. The screening cage, having a hole for the outgoing particles and a slit for the incident beam, is kept at a negative potential. Pictures of the two parts of the target chamber, here schematically indicated, are shown in ref. 8.

rate of the integrator does not change with the negative potential if the magnitude of the latter is greater than about 150 V, even if the beam, after passing a foil, hits the chamberwall. Generally the voltage was –300 V.

When a target with thin foil backing is used it is necessary to apply a device for catching the whole beam or a constant part of it. Fig. 1 A shows schematically such a device for different angles φ. For $\varphi > 10°$ a measuring plate is simply placed behind the foil. For $\varphi \leq 10°$, when the directions of the incoming beam and the outgoing particles are about the same, a small-meshed metal net is put in front of the target. A fixed part of the charge of the beam is given to the net and a fixed part of the beam hits the target. The counting rate of the current integrator is thus proportional to the intensity of the bombarding beam. When the beam has passed the net and the foil, it must not strike any part of the screening cage, for then the latter is not effective due to secondary electrons emitted from it. A special cage was used when measuring with the net. Another way to place the metal net—behind the foil—was also investigated, but did not give satisfactory results

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